

# Potential distribution and priority conservation areas for the endangered Caatinga Howler Monkey *Alouatta ululata*, Northeastern

## 5 Brazil

ROBÉRIO FREIRE FILHO and JORGE M. PALMEIRIM

ROBÉRIO FREIRE FILHO (Corresponding author) Programa de Pós-Graduação em Biologia Animal, Universidade Federal de Pernambuco, Centro de Biociências, Departamento de Zoologia. Av. Prof. Moraes Rego, 1235, Cidade Universitária. Cep. 50670-420. Recife-Pernambuco. Brasil. E-mail freirefilho@outlook.com

JORGE M. PALMEIRIM Departamento de Biologia Animal, cE3c - Centro de Ecologia, Evolução e Alterações Ambientais. Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal

15 **Abstract** The Caatinga of NE Brazil is the largest and most diverse seasonally dry tropical forest in the Americas and is home to numerous endemic species. It is declining alarmingly but only 1.2% is under full protection, so there is an urgent need to expand the protected network. The Caatinga howler monkey (*Alouatta ululata*) is an endangered species nearly endemic to the Caatinga, with a good potential as an umbrella species to protect much of its biodiversity. Using all available distribution data and own surveys we applied Maxent and Zonation spatial modelling to identify the range and priority conservation areas for *A. ululata*, maximizing habitat quality and connectivity, while minimizing conservation constraints. The top 10% priority areas cover 34,400 Km<sup>2</sup> and mostly coincide with good remnants of Caatinga. Only in the northern part of the species range priority areas are protected, so it is essential to create new protected areas in the center and south of the range. Maxent modelling shows that the species depends on good tree cover, but even inside protected areas we observed recent deforestation, illustrating the urgency to improve management. Maxent also revealed that aridity limits the range of the species, so the ongoing aridification of the Caatinga is a menace to its future. In conclusion, the protection of the threatened *A. ululata* requires establishing new protected areas in priority regions and improving management in those already classified. This challenge is also an opportunity for the conservation of important biodiversity sharing the priority areas of the species.

**Keywords** Maxent, Primate, Species Distribution modelling, Zonation

## Introduction

Located in Northeastern Brazil, the Caatinga covers about 735,000 km<sup>2</sup> (Leal et al., 2005), and is considered by many as one of the World's major wilderness areas (Aguiar et al., 2002). It is the largest and most diverse seasonally dry tropical forest in the Americas and harbors large numbers of endemic species (DRYFLOR). However, its natural vegetation has been declining at an alarming rate (Beuchle et al., 2015) due to land use intensification (Aguiar et al., 2002; Leal et al., 2005). There is an urgent need to take conservation measures to protect the Caatinga, where only 1.2% of the area is under full protection (DRYFLOR, 2016). Protection areas need to be greatly expanded, and charismatic species, such as large primates, can facilitate this process (Ducarme et al, 2013), as they function as umbrella species for the conservation of valuable but more discreet biodiversity in their range. One of the species with greatest potential for this role is the Caatinga howler monkey (*Alouatta ululata*) a threatened large primate requiring vast areas of suitable habitat to maintain viable populations.

The Caatinga howler monkey has an Endangered status due to its small and declining population, consequences of loss of tree cover, habitat fragmentation and hunting (Oliveira & Kierulff, 2008). Most of the species' range is in the Caatinga although it extends into the Cerrado (Oliveira & Kierulff, 2008), but its limits are poorly known, which is a major constraint for the planning of conservation measures (Oliveira & Kierulff, 2008). Species distribution modelling (SDM) is a tool to map geographic distributions and study how environmental variables influence them (Miller, 2010). It is widely applied in conservation science and its models may support the selection of areas for conservation (Araújo et al., 2002). The most common approach in SDM is maximum-entropy modelling, often applied using Maxent software (Phillips et al., 2006).

The identification of priority areas for conservation of species is a prime step to build conservation plans (Pressey et al., 2007). The past few years have seen the development of computational tools to carry out this process of prioritization taking into consideration factors such as habitat quality, connectivity and conservation cost (Kukkala & Moilanen, 2012). C-Plan (Pressey et al., 2009), Marxan (Watts et al., 2009) and Zonation (Moilanen et al., 2005) are examples of approaches and packages developed for conservation prioritization. The general objective of all these packages is quite similar, although the strategy to reach them varies. For example, Zonation, the package used in this study, prioritizes landscapes by iteratively removing the least valuable remaining areas while accounting for connectivity and generalized complementarity (Moilanen et al., 2011).

The overarching objective of this project is to make spatially explicit analyses that contribute to the planning of measures to conserve *A. ululata* and the ecosystems to which it is associated. Our

specific objectives were (i) to carry out field surveys to collect information on the distribution of the species; (ii) to identify areas where further surveys are needed; (iii) to develop a model to generate a potential distribution species' map and understand the environmental determinants of this distribution; (iv) to identify the areas with most potential for the conservation of the species, (v) and to determine the degree of coverage of the priority areas by existing protection areas. Finally, (vii) we use our results to make spatially explicit recommendations for actions needed to improve the conservation of *A. ululata* and of the many species that depend on the same Caatinga habitats.

## Study area

The study area includes the known range of *A. ululata*, across the states of Maranhão, Piauí and Ceará (Fig.1). In the spatial analysis we included not only the area encompassing all the known locations for the species, but also a 30-km wide buffer around it. The aim of this addition was to identify areas that may be suitable for the species but that are outside its currently known range.

## MethodsData Collection

We compiled existing information on the distribution of *A. ululata*, mostly collected between 2004 and 2010 by the National Center for Research and Conservation of Brazilian Primates (CPB/ICMBio). The number of direct observations by researchers is very low (20 records), so we also used reports obtained in CPB/ICMBio interviews (112 reports). Interview-based distribution analysis can complement direct monitoring data in the case of easily identifiable species (Anadón et al., 2010; Brittain et al., 2018). We also carried out surveys in two regions where information was scarce (August 2016 to May 2017) (Fig. 1). We interviewed 112 farmers and hunters that lived or worked close to areas with natural vegetation. To minimize biased answers we hid that *A. ululata* was the focus of our interviews. We first asked about other mammals present in the region and only after that about *A. alouata*. We only interviewed persons comfortable with the the study and respected the interview ethical code of the British Sociological Association ([https://www.britisoc.co.uk/media/24310/bsa\\_statement\\_of\\_ethical\\_practice.pdf](https://www.britisoc.co.uk/media/24310/bsa_statement_of_ethical_practice.pdf)).

Some records based on interviews were initially referenced with coordinates of the place of the interview, usually farmhouses. We replaced these coordinates by those of the nearest area with a natural environment, within a 2-km buffer around the original coordinates (approximately the distance at which the vocalization of the species can be heard). Points without natural environments inside the 2-km buffer were excluded. This procedure adds locational uncertainty, but Maxent modelling can make useful predictions even when the occurrence data includes a moderate level of locational error (Graham et al., 2008). Our initial database included 184 occurrences, 52 from our surveys and 132 from CPB/ICMBio. However, to minimize problems associated with spatial biases

in sampling, we used spatial filtering (Kramer-schadt et al., 2013), reducing the number of occurrences in oversampled areas by using only one in a radius of 5 km. This filtering procedure reduced the number of occurrences used in the modeling to 117 (20 direct observations and 70 reports from CPB/ICMBio, and one observation and 26 reports from our surveys).

### **Modelling of potential distribution**

To identify variables influencing the distribution of *A. ululata* and generate a distribution map, we used Maxent software (Phillips et al., 2006). The choice of environmental variables was guided by the species' biology; *A. ululata* is arboreal, feeds on leaves, fruits and other plant parts, and lives in a semi-arid region influenced by strongly seasonal rainfall and high temperatures. We expected areas with higher precipitation to be more suitable during the most likely critical period of the year, the dry season. Furthermore, we hypothesized that tree cover and tree height would influence suitability, and that areas with rugged terrain would be more suitable since terrain ruggedness tends to be an obstacle to habitat destruction and to provide some protection from hunting. With the help of a matrix of correlations between all candidate variables, we selected a set of six predictors (Table 1) that were not highly correlated ( $|r| < 0.70$ ) (Rainho & Palmeirim, 2013) and that were biologically meaningful.

Prior to running Maxent all layers were converted to the WGS 1984 geographical coordinate system and to a cell size of 30 arc seconds (about 1 km<sup>2</sup>), using IDRISI Selva (Eastman, 2012) and QGIS 2.8 (QGIS Development Team, 2016). In Maxent we used the following settings: convergence threshold (10<sup>-5</sup>), maximum iterations (500), regularization multiplier (1), max number of background points (104), linear, quadratic, product and hinge features, random seed generation and 50 replicates. The resulting map is in logistic format with the probability of presence for each cell ranging between 0 and 1 (Phillips, 2008). To select a suitability threshold for the potential distribution map we used the methodology described in Rainho and Palmeirim (2013), which allows the selection of the smallest area including most occurrences. The area selected was that corresponding to the Maxent suitability threshold 70%, which encompassed 83% of the occurrences (Supplementary Fig. S1); above this threshold the inclusion of more occurrences would force the addition of a disproportionately large area.

### **Prioritizing areas for conservation of *Alouatta ululata***

We used the Zonation package (Moilanen et al., 2005) to prioritize areas for the conservation of *A. ululata*. Zonation generates a priority map that can be used to inform decision-making. It allows the consideration of cost efficiency in this prioritization, through the inclusion of a “cost layer”. We assumed that conservation cost efficiency is higher in areas with fewer anthropogenic constraints, and

thus generated a single “constraints” layer combining three thematic layers: human population density, proximity to roads, and anthropic areas (i.e. urban and farmland areas). These three layers, described in Table 1, were given equal weight in the generation of the “constraints” layer. Zonation assigned this layer negative weights and combined it with the map of potential distribution of *A. ululata* generated with Maxent.

In Zonation we selected “distribution smoothing” as the aggregation method. It considers fragmentation to be undesirable and thus retains areas that are well interconnected. The size of the smoothing kernel used was 6 km, a value based on the distances often crossed by various *Alouatta* species outside their usual home-ranges (Glander, 1992; Crockett, 1998). As a cell removal rule we used “core-area Zonation”, because it is appropriate when importance is given to core-areas, i.e. locations with the highest suitability in terms of abundance or high probability of occurrence (Moilanen et al., 2017). To avoid losing valuable areas and to keep structural connectivity we selected the options “add edge points” and “edge removal” (Moilanen et al., 2017).

To identify the priority regions lacking protection, we overlaid the Zonation map with the existing protected areas. Finally, we used a map of forest loss between 2000 and 2014 (Hansen et al., 2013) to identify recent deforestation in priority areas.

## Results

The average test area under the curve (AUC) for the Maxent distribution model of *A. ululata* was 0.857 and the standard deviation 0.032, indicating a high efficiency distinguishing presence from random background locations (Fig. 2). The variables with greatest percent contributions to build the potential distribution model were percentage tree cover, precipitation of driest quarter (bio17) and aridity index (Table 2). The jackknife analysis corroborates these results (Table 2). Probability of presence increases with tree cover, canopy height and terrain roughness (Fig. 3). In the case of the climatic variables (aridity, precipitation in driest quarter and precipitation seasonality) the highest probability of occurrence tends to be in the intermediate values (Fig. 3).

Results of the Zonation prioritization are shown in the map on Fig. 4A. For graphical clarity, we only show two levels of priority: high priority (the best 20%) and top priority (the best 10%). These priority areas can be separated in four regions, which are ecologically quite distinct: (1) Mangroves, in the Parnaíba river mouth; (2) Enclaves, encompassing the humid enclaves of Northwest Ceará and Northern Piauí; (3) Caatinga, a vast region fully inside the Caatinga biome; and (4) Border, located along the border between Piauí and Maranhão (Fig. 4A).

About 21% of the most important areas for the conservation of the species are inside legally protected areas (Fig. 4A). However, the coverage of priority regions by these protected areas is very uneven; important parts of Mangrove and Enclaves have some level of legal protection, whereas  
165 Border and caatinga are virtually unprotected (Table 3).

Although the recent (2000-2014) loss of tree cover is scattered, it occurred throughout the high priority areas, including inside protected areas. In some regions of Northern Piauí (Enclaves), deforestation is more widespread and there are larger continuous deforested patches (Fig. 4B). Overall, about 3.8% of the best areas for the conservation of *A. ululata* has been deforested in the  
170 recent past (Table 3).

## Discussion

### Potential distribution of *Alouatta ululata* and variables that influence the probability of occurrence of the species

A visual analysis and the means number of the presence points in higher levels of probability of  
175 presence show a good correspondence between the distribution and density of the occurrences and the Maxent map. However, there are suitable areas without occurrences, which may be due to local extinctions (e.g. due to hunting), or a lack of survey effort (Oliveira & Kierulff, 2008). There are also a few occurrences in areas with low Maxent suitability, which can be explained by the extensive loss of natural habitat in the region (Oliveira & Kierulff, 2008).

180 An isolated population inhabits a small humid enclave in Acopiara, Ceará, separated from the range of the species by over 100 km of unsuitable dry Caatinga (Fig. 1) (Oliveira et al, 2007). It is probably a remnant of a broader distribution of the species when humid forest dominated the region (Carmignotto et al., 2012), but it may also result from an ancient human introduction.

185 The eastern limit of the range of *A. ululata* is clear and defined by the high aridity conditions in central Ceará. However, the western limit is ill defined and possibly explained too wet conditions prevailing in Maranhão. Moreover, competition with *Alouatta belzebul* a close species occurring further west, may help shaping the western limit of the range of *A. ululata*. In fact, it is unclear if the two taxa are distinct species or just differentiated populations of the same species (Viana et al., 2015).

190 The variables that entered the Maxent model are coherent with the biology of the species (Oliveira & Kierulff, 2008). Percentage tree cover was the most important of these variables and suitability was very low up to approximately 50% tree cover, which is probably explained by the marked arboreal habits of the species (Oliveira & Kierulff, 2008). The folivorous-frugivorous diet of *A. ululata* may also contribute to make the species dependent on dense tree cover, as trees are the

main food source (Oliveira & Kierulff, 2008). Moreover, the results suggest that *A. ululata* prefers  
195 tall forest, even though they occupy a variety of woodland types (Oliveira & Kierulff, 2008).

The second and third most influential variables in the model are both climatic and related:  
aridity index and precipitation in the driest quarter (Bio17). The results show that regions with an  
extreme dry season are unsuitable habitats, suggesting vulnerability to the ongoing aridification of  
the Caatinga (Torres et al., 2017): it is predicted that at the end of the century temperatures may be  
200 up to 3.5-4.5°C higher and rainfall 40-50% lower (PBM, 2013).

### **Priority areas for conservation and current level of conservation**

The priority areas identified with Zonation (Fig. 4A) should conciliate a high habitat suitability,  
identified by Maxent, with good connectivity and low conservation constraints. This should make our  
results a good basis for conservation planning. However, it is important to be aware that both Maxent  
205 and Zonation modelling are affected by sources of error, such as inaccuracies in species occurrences  
and environmental layers, that create uncertainty (Graham et al., 2008; Moilanen et al., 2017). New  
and better models should be generated as more information on species or better environmental layers  
become available, and management decisions may have to be adjusted to the new results. However,  
the inevitable uncertainty associated to models should not be an obstacle to carefully using them to  
210 plan conservation action; in the presence of rapid environmental change the risks of inaction are  
probably greater than those of judiciously using models (Wiens et al., 2009).

The identified priority areas encompass ecologically distinct regions. For example, the *A.*  
*ululata* population that inhabits the mangroves of the Parnaíba river mouth (Mangrove), has a unique  
ecology (e.g. a diet composed of mangrove plants). The groups that inhabit the Enclave region of  
215 Ceará live mostly in humid enclaves with open ombrophilous forest. Adaptations to these different  
environments may have resulted in populations of *A. ululata* with distinct behaviors, ecologies, gene  
pools and even morphologies. It is clearly desirable to protect the various ecological contexts in which  
the species is present. Virtually all priority areas with a protected status are in the northern part of the  
species range. The south, including the region with most occurrences, is completely unprotected. This  
220 worrisome situation is in line with the scarcity of protected areas in the Caatinga (de Marques &  
Peres, 2015; DRYFLOR, 2016).

It is important to note that, even on paper, the level of conservation provided by most protected  
areas in the range of *A. ululata* is very slight. Of the nine relevant protected areas only two are "full  
protection" units (Uajajara and Sete Cidades National Parks) having nature preservation as a main  
225 objective and only allowing the indirect use of natural resources (MMA, 2016). All other conservation  
units allow sustainable use of natural resources (MMA, 2016), which needs to be well managed to

avoid damaging habitats. However, a serious lack of human and financial resources results in highly insufficient management. Moreover, in this region awareness of the protected areas is extremely low (Drummond et al., 2009).

Our analysis revealed that deforestation is ongoing throughout most of the priority areas, even inside protected areas (Fig. 4B), in line with the general trend of tree cover loss in the Caatinga (Beuchle et al., 2015). The situation is only better in federally protected National Parks, where we did not identify recent deforestation. It is thus evident that protected areas currently make a very small contribution to the protection of *A. ululata*, and of the other natural values of the Caatinga.

## Conclusions and Conservation consequences

The results of the spatial analyses performed in this paper suggest a variety of lines of action to preserve *A. ululata*. These actions vary across the range of the species, as shown in Fig. 4C, and are discussed here.

Maxent modelling indicates that the range of *A. ululata* includes poorly surveyed areas where the presence of the species has not been confirmed. Moreover, the Zonation analysis shows that some of these areas have a high level of conservation priority. It is thus urgent to survey these areas and despite the recent surveys by CPB/IBAMA, the absence of information is still flagrant (Fig. 4C).

The Maxent analysis indicates that good tree cover and levels of aridity lower than those prevailing in the Caatinga region are critical for the maintenance of *A. ululata*, suggesting that the species is affected by both deforestation and climate change. Unfortunately, tree cover is declining (Beuchle et al., 2015), even in protected areas (Fig. 4C), and arid conditions are increasing (Torres et al., 2017).

Our results show that the legal protection of the areas suitable for the protection of *A. ululata* is very uneven. The central and southern areas of the species' range, which includes some of the potentially best areas for its protection, is not included in any protected area. It is important to fill this gap by designating new state, federal and private protected areas, especially in the larger contiguous priority areas (Fig. 4C). Moreover, it is critical to improve the management of the existing protected areas. Knowledge on the biology of *A. ululata* is still insufficient to plan efficient management measures. Therefore, in addition to survey work to clarify the status of the species, it is important to research aspects of its ecology that are critical to conservation.

The priority areas identified by the Zonation models mostly coincide with good remnants of Caatinga, which are also important for a substantial part of the great biodiversity of this biome, threatened by habitat destruction but poorly covered by protected areas (DRYFLOR, 2016). Due to



its large body size, the conservation of viable populations of *A. ululata* requires the maintenance of large areas of well-preserved habitat, making it a good umbrella species, with potential to contribute to the protection of the rich biodiversity that shares its threatened habitat.

## Acknowledgements

Study funded by Rufford Foundation grant 19646-1. RFF holds a FACEPE scholarship (IBPG-1236-2.05/16). We are thankful to collaborating rural communities, and to Thieres Pinto, Gabriela Linhares, Andressa Fraga and Nádia Freitas for assistance in the field. Marcos Fialho and Leandro Jerusalinsky (CPB-ICMBio) kindly provided presence points of the species.

## Author contributions

RFF and JMP conceived and designed the study and wrote the article. RFF performed the field work and analysed the data.

## References

- Aguiar, J., Lacher, T.E. & da Silva, J.M.C. (2002) The Caatinga. In *Wilderness: Earth's last wild places* (eds R.A. Mittermeier, C.G. Mittermeier, P. Robles Gil, J. Pilgrim, G.A.B. da Fonseca, T. Brooks & W.R. Konstant), pp. 174-181. Cemex, México, MX.
- Araújo, M.B., Williams, P.H., & Fuller, R.J. (2002) Dynamics of extinction and the selection of nature reserves. *Proceedings of the Royal Society of London B: Biological Sciences*, 269, 1971-1980.
- Anadón, J.D., Giménez, A. & Ballestar, R. (2010) Linking local ecological knowledge and habitat modelling to predict absolute species abundance on large scales. *Biodiversity and Conservation*, 19, 1443-1454.
- Balk, D.L., Deichmann, U., Yetman, G., Pozzi F., Hay, S.I. & Nelson, A. (2006) Determining global population distribution: methods, applications and data. *Advances in Parasitology*, 62, 119-156.
- Bean, W.T., Stafford, R. & Brashares, J.S. (2011) The effects of small sample size and sample bias on threshold selection and accuracy assessment of species distribution models. *Ecography*, 35, 250-258.

- Beuchle, R., Grecchi, R.C., Shimabukuro, Y.E., Seliger, R., Eva, H.D., Sano, E. & Achard, F. (2015) Land cover changes in the Brazilian Cerrado and Caatinga biomes from 1990 to 2010 based on a systematic remote sensing sampling approach. *Applied Geography*, 58, 116-127.
- Brittain, S., Ngo Bata, M., De Ornellas, P., Milner-Gulland, E. & Rowcliffe, M. (2018)  
 290 Combining local knowledge and occupancy analysis for a rapid assessment of the forest elephant *Loxodonta cyclotis* in Cameroon's timber production forests. *Oryx*, 1-11.
- Carmignotto, A.P., & Astúa, D. (2017) Mammals of the Caatinga: Diversity, Ecology, Biogeography, and Conservation. In *Caatinga: the largest tropical dry forest region in South America* (eds J.M.C da Silva, I.R Leal & M Tabarelli), pp. 211-254. Springer, Cham, Switzerland.
- 295 Carmignotto, A.P., Vivo, M.D. & Langguth, A. (2012) Mammals of the Cerrado and Caatinga: distribution patterns of the tropical open biomes of central South America. In *Bones, Clones, and Biomes: The History and Geography of Recent Neotropical Mammals* (eds B.D. Patterson & L.P. Costa), pp. 307-350. University of Chicago Press, Chicago, USA.
- Ceballos, G. (1995) Vertebrate diversity, ecology, and conservation in neotropical dry forests.  
 300 In *Seasonally dry tropical forest* (eds S. Bullock, E. Medina & H. Mooney), pp.195-220. Cambridge University Press, Cambridge, UK.
- Crockett, C.M. (1998) Conservation biology of the genus *Alouatta*. *International Journal of Primatology*, 19, 549-578.
- de Marques, A.A.B. & Peres, C.A. (2015) Pervasive legal threats to protected areas in Brazil.  
 305 *Oryx*, 49, 25-29.
- Ducarme, F., Luque, G.M. & Courchamp, F. (2013) What are “charismatic species” for conservation biologists. *BioSciences Master Reviews*, 10, 1-8.
- Drummond, J.A., Franco, J.L.A. & Ninis, A.B. (2009) Brazilian federal conservation units: a historical overview of their creation and of their current status. *Environment and History*, 15, 463-  
 310 491.

- DRYFLOR (2016) Plant diversity patterns in neotropical dry forests and their conservation implications. *Science*, 353, 1383-1387.
- Eastman, J.R. (2012) *IDRISI Selva Manual Version 17.01*. Clark University.
- Elith, J. & Leathwick, J.R. (2009) Species distribution models: ecological explanation and  
 315 prediction across space and time. *Annual Review of Ecology, Evolution, and Systematics*, 40, 677-697.
- Glander, K.E. (1992) Dispersal patterns in Costa Rican mantled howling monkeys. *International Journal of Primatology*, 13, 415-436.
- Graham, C.H., Elith, J., Hijmans, R.J., Guisan, A., Townsend Peterson, A., Loiselle, B.A. &  
 320 NCEAS, Predicting Species Distributions Working Group. (2008) The influence of spatial errors in species occurrence data used in distribution models. *Journal of Applied Ecology*, 45, 239-247.
- Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A. & Tyukavina, A. (2013) High-resolution global maps of 21st-century forest cover change. *Science*, 342, 850-853.
- Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G. & Jarvis, A. (2005) Very high resolution  
 325 interpolated climate surfaces for global land areas. *International Journal of Climatology*, 25, 1965-1978.
- Hijmans, R.J., Guarino, L. & Mathur, P. (2012) DIVA-GIS Manual (version 7.5). <http://www.diva-gis.org>. [accessed 22 June 2016].
- Kramer-schadt, S., Niedballa, J., Pilgrim, J.D., Schroder, B., Lindenborn, J., Reinfelder, V. et  
 330 al. (2013) The importance of correcting for sampling bias in MaxEnt species distribution models. *Diversity and Distributions*, 19, 1366-1379.
- Kukkala, A.S. & Moilanen, A. (2012) Core concepts of spatial prioritisation in systematic conservation planning. *Biological Reviews*, 88, 443-464.
- Leal, I.R., Silva J.M.C., Tabarelli, M. & Lacher, T.E. (2005) Changing the course of  
 335 biodiversity conservation in the Caatinga of Northeastern Brazil. *Conservation Biology*, 19, 701-706.

- Lehtomäki, J. & Moilanen, A. (2013) Methods and workflow for spatial conservation prioritization using Zonation. *Environmental Modelling & Software*, 47, 128-137.
- Miller, J. (2010) Species distribution modeling. *Geography Compass*, 4, 490-509.
- MMA. (2016) Sistema Nacional de Unidades Conservação - SNUC.  
 340 <http://www.mma.gov.br/areas-protegidas/sistema-nacional-de-ucs-snuc>. [accessed 20 June 2017].
- Moilanen, A., Anderson, B.J., Eigenbrod, F., Heinemeyer, A., Roy, D.B., Gillings, S. et al. (2011) Balancing alternative land uses in conservation prioritization. *Ecological Applications*, 21, 1419-1426.
- Moilanen, A., Franco, A.M.A., Early, R.I., Fox, R., Wintle, B. & Thomas, C.D. (2005)  
 345 Prioritizing multiple-use landscapes for conservation: methods for large multi-species planning problems. *Proceedings of the Royal Society B: Biological Sciences*, 272, 1885-1891.
- Moilanen, A., Pouzols, F.M., Meller, L., Veach, V., Arponen, A., Leppänen, J. & Kujala, H. (2017) *Spatial conservation planning methods and software Zonation Version 4 User Manual*.
- Oliveira, M.M., Ferreira, J.G., Mota, G.L.S. & Soares, S.G. (2007) Mapeamento das áreas de  
 350 ocorrência de *Alouatta ululata* - Etapa Ceará. In *A Primatologia do Brasil, volume 10* (ed J.C. Bicca-Marques), pp. 151-161, Sociedade Brasileira de Primatologia, Porto Alegre, BR.
- Oliveira, M.M. & Kierulff, M.C.M. (2008) *Alouatta ululata*. The IUCN red list of threatened species. <http://dx.doi.org/10.2305/IUCN.UK.2008.RLTS.T918A13094890.en>. [accessed 20 June 2017].
- 355 PBMC. (2013) *Executive summary: scientific basis of climate change - Contribution from Grupo de Trabalho 1 (GT1, acronym for the Working Group 1) to the Primeiro Relatório de Avaliação Nacional sobre Mudanças Climáticas (RANI) of the Painel Brasileiro de Mudanças Climáticas (PBMC)*. Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ, Brazil.

- Pearson, R.G., Raxworthy, C.J., Nakamura, M. & Peterson, A.T. (2007) Predicting species  
360 distributions from small numbers of occurrence records: A test case using cryptic geckos in  
Madagascar. *Journal of Biogeography*, 34, 102-117.
- Phillips, S. (2008) *A brief tutorial on maxent*. AT&T Research.
- Phillips, S.J., Anderson, R.P. & Schapire, R.E. (2006) Maximum entropy modeling of species  
geographic distributions. *Ecological Modelling*, 190, 231-259.
- 365 Pressey, R.L., Cabeza, M., Watts, M.E., Cowling, R.M. & Wilson, K.A. (2007) Conservation  
planning in a changing world. *Trends in Ecology & Evolution*, 22, 583-592.
- Pressey, R.L., Watts, M.E., Barrett, T.W. & Ridges, M.J. (2009). The C-Plan conservation  
planning system: origins, applications, and possible futures. In *Spatial conservation prioritization*  
(eds A. Moilanen, K.A. Wilson & H. Possingham), pp 211–234. Oxford University Press, Oxford,  
370 UK
- QGIS Development Team. (2016). QGIS Geographic Information System. Open Source  
Geospatial Foundation. <http://www.qgis.org/en/site/> [accessed 24 May 2017].
- Rainho, A. & Palmeirim, J.M. (2013) Prioritizing conservation areas around multispecies bat  
colonies using spatial modeling. *Animal Conservation*, 16, 438-448.
- 375 Richard-Hansen, C., Vié, J.C. & Thoisy, B. (2000) Translocation of red howler monkeys  
*Alouatta seniculus* in French Guiana. *Biological Conservation*, 93, 247-253.
- Riley, S.J., DeGloria, S.D. & Elliot, R. (1999) A terrain ruggedness index that quantifies  
topographic heterogeneity. *Intermountain Journal of Science*, 5, 23-27
- Simard, M., Pinto, N., Fisher, J.B. & Baccini, A. (2011) Mapping forest canopy height globally  
380 with spaceborne lidar. *Journal of Geophysical Research*, 116, 1-12.
- Torres, R.R., Lapola, D.M. & Gamarra, N.L.R. (2017) Future Climate Change in the Caatinga.  
In *Caatinga: The Largest Tropical Dry Forest Region in South America* (eds J.M.C. da Silva, I.R.  
Leal & M. Tabarelli), pp. 383-410, Springer, Cham, Switzerland.

- Viana, M.C., Bonvicino, C.R., Ferreira, J.G., Jerusalinsky, L., Langguth, A. & Seuánez, H.  
 385 (2015) Understanding the relationship between *Alouatta ululata* and *Alouatta belzebul* (Primates: Atelidae) based on cytogenetics and molecular phylogeny. *Oecologia Australis*, 19, 173-182.
- Watts, M.E., Ball, I.R., Stewart, R.S., Klein, C.J., Wilson, K., Steinback, C. et al. (2009) Marxan with Zones: software for optimal conservation based land-and sea-use zoning. *Environmental Modelling & Software*, 24, 1513-1521.
- 390 Wiens, J.A., Stralberg, D., Jongsomjit, D., Howell, C.A. & Snyder, M.A, (2009) Niches, models, and climate change: Assessing the assumptions and uncertainties. *Proc. Natl. Acad. Sci. U.S.A.*, 106, 19729 –19736.
- Zomer, R.J., Trabucco, A., Bossio, D.A. & Verchot, L.V. (2008) Climate change mitigation: a spatial analysis of global land suitability for clean development mechanism afforestation and  
 395 reforestation. *Agriculture, Ecosystems and Environment*, 126, 67-80.

### Biographical sketches

ROBÉRIO FREIRE FILHO is specializes in conservation of Endangered primate species. His research  
 400 focuses on ecology, behavior, ethnobiology, conservation planning, modelling and climate changes. JORGE M. PALMEIRIM 's research focuses on contributing to the knowledge required for science based conservation and management at the global, ecosystem and species levels. He is personally and professionally highly committed to the preservation of biological diversity.

405

TABLE 1 Information about predictive variables used in our analysis.

	Name	Description	Source
Maxent variables	Percentage tree cover	Defined as canopy closure for all vegetation more than 5m height.	Global Forest Change 2000 - 2014 (Hansen et al., 2013)
	Aridity Index	Rainfall deficit for potential vegetative growth. Higher values represent greater aridity	CGIAR-CSI ( Zomer et al., 2008)
	Bio17	Precipitation of Driest Quarter	WorldClim 1.4 (Hijmans et al., 2005)
	Bio15	Precipitation Seasonality (standard deviation of monthly precipitation expressed as percentages)	WorldClim 1.4 (Hijmans et al., 2005)
	Forest Canopy Height	Global 1Km Forest canopy Height	SDAT ( <a href="http://webmap.ornl.gov/wcsdown/wcsdown.jsp?dg_id=10023_1">http://webmap.ornl.gov/wcsdown/wcsdown.jsp?dg_id=10023_1</a> ) (Simard et al., 2011)
	Roughness index	Quantitative measurement of terrain heterogeneity generated in QGIS using SRTM3 data	Shuttle Radar Topography Mission 3 (SRTM3) ( <a href="http://earthexplorer.usgs.gov/">http://earthexplorer.usgs.gov/</a> ) (Riley et al., 1999)
Constraint layers	Anthropic areas	Land cover map from GlobCover project. All anthropic categories (cropland and urban) were joined in a single class	Globcover ( <a href="http://due.esrin.esa.int/page_globcover.php">http://due.esrin.esa.int/page_globcover.php</a> )
	Influence of roads	Buffer of road influence 18 km to each side. This distance was selected subjectively visually analyzing the land cover along roads in the study area	<u>IBGE</u> ( <a href="http://geoftp.ibge.gov.br/mapeamento_sistematico/base_vetorial_continua_escala_250mil/">http://geoftp.ibge.gov.br/mapeamento_sistematico/base_vetorial_continua_escala_250mil/</a> )
	Population density	Global Rural-Urban Mapping Project, Version 1 (GRUMPv1): Population Density Grid	Center for International Earth Science Information Network – CIESIN ( <a href="http://dx.doi.org/10.7927/H4R20Z93">http://dx.doi.org/10.7927/H4R20Z93</a> ) (Balk et al., 2006)

TABLE 2 Maxent results.

Variables	Percent contribution	Permutation importance	Training gain without	Training gain with only	Test gain without	Test gain with only	AUC without	AUC with only
Percent tree cover	<u>55.411</u>	<u>51.928</u>	<u>0.789</u>	<u>0.502</u>	<u>0.714</u>	<u>0.475</u>	<u>0.814</u>	<u>0.751</u>
Bio17	<u>15.786</u>	<u>16.139</u>	<u>1.009</u>	0.145	<u>0.909</u>	0.149	<u>0.846</u>	0.661
Aridity Index	<u>10.516</u>	<u>17.884</u>	1.043	<u>0.363</u>	0.949	<u>0.359</u>	0.847	<u>0.727</u>
Roughness Index	7.102	1.778	<u>1.025</u>	0.140	0.966	0.120	0.854	0.622
Bio15	5.179	7.624	1.025	0.041	<u>0.907</u>	0.042	<u>0.845</u>	0.578
Forest Canopy Height	6.004	4.644	1.031	<u>0.204</u>	0.985	<u>0.169</u>	0.849	<u>0.663</u>

TABLE 3 Protected area and recent forest loss in each of the four priority regions mentioned in the text.

	Inclusion in protected areas		Forest loss (2000 to 2014)	
	Percentage (%)	Km <sup>2</sup>	Percentage (%)	Km <sup>2</sup>
Mangrove	69	2,359.028	8	272.640
Enclave	50	9,814.051	4	776.058
Caatinga	10	63.619	2	926.061
Border	3	15,519.234	6.7	1,039.788
Total of four regions	21	27,755.932	3.8	3,216.066

415

420



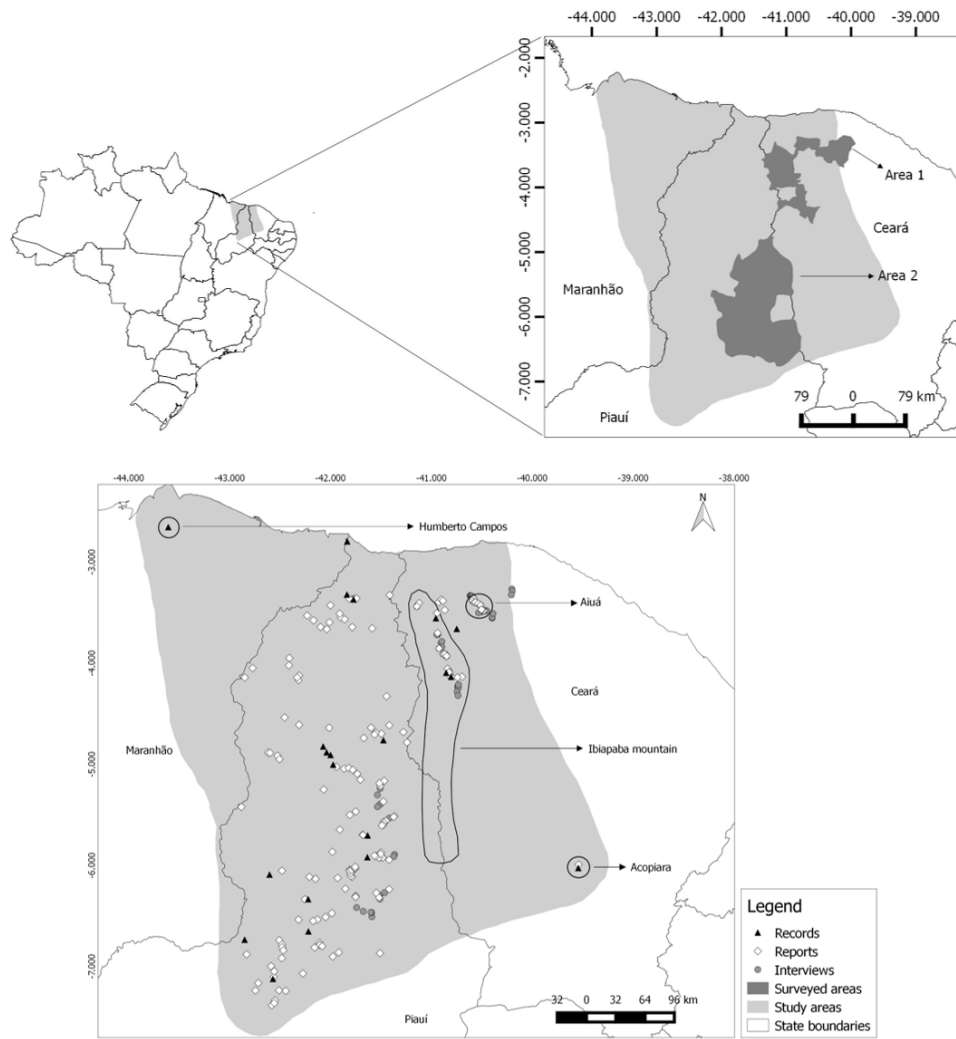


FIG. 1 Location of study area, surveyed regions and sites where the species has been recorded.

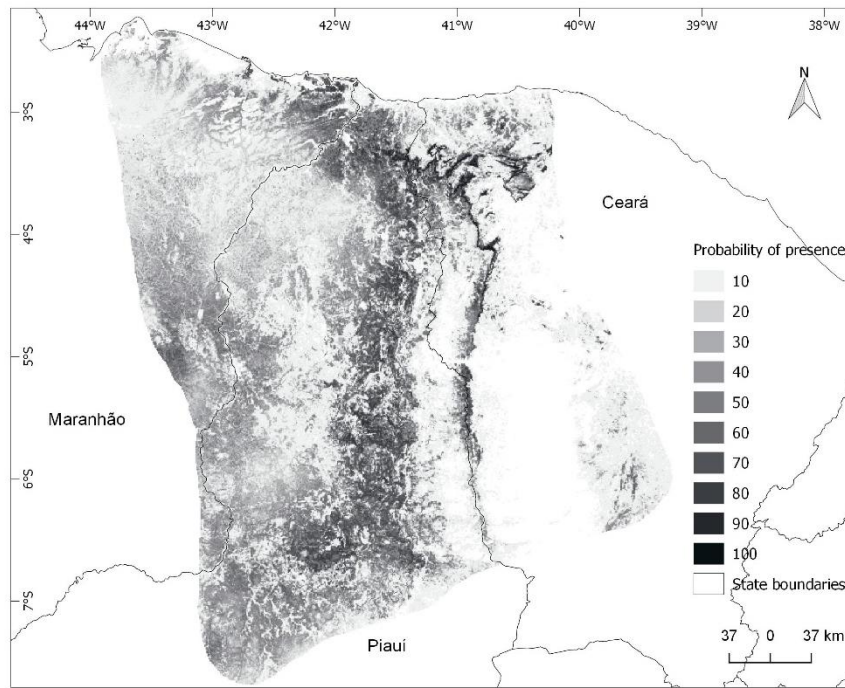


FIG. 2 Probability of occurrence of the Caatinga howler monkey, as predicted by the Maxent model.

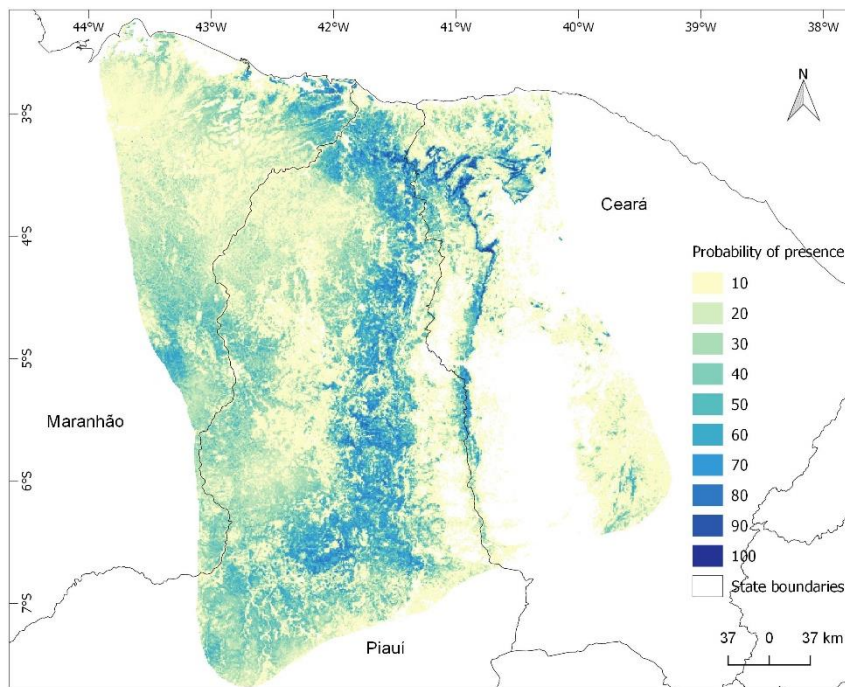


FIG. 2 Probability of occurrence of the Caatinga howler monkey, as predicted by the Maxent model.

430

435

440

445

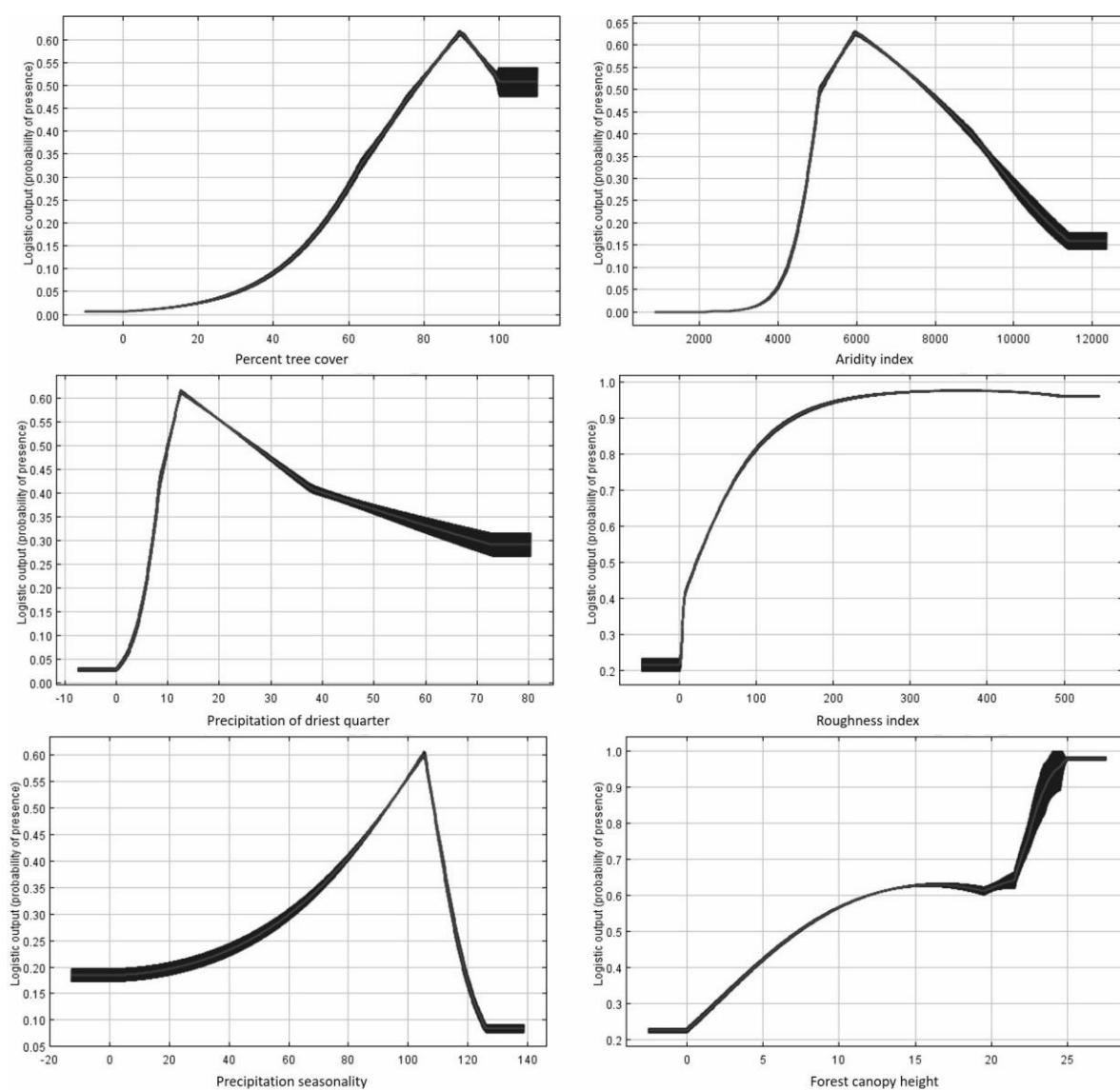


FIG. 3 Curves showing the relationship of each environmental variable with the probability of presence of the species.

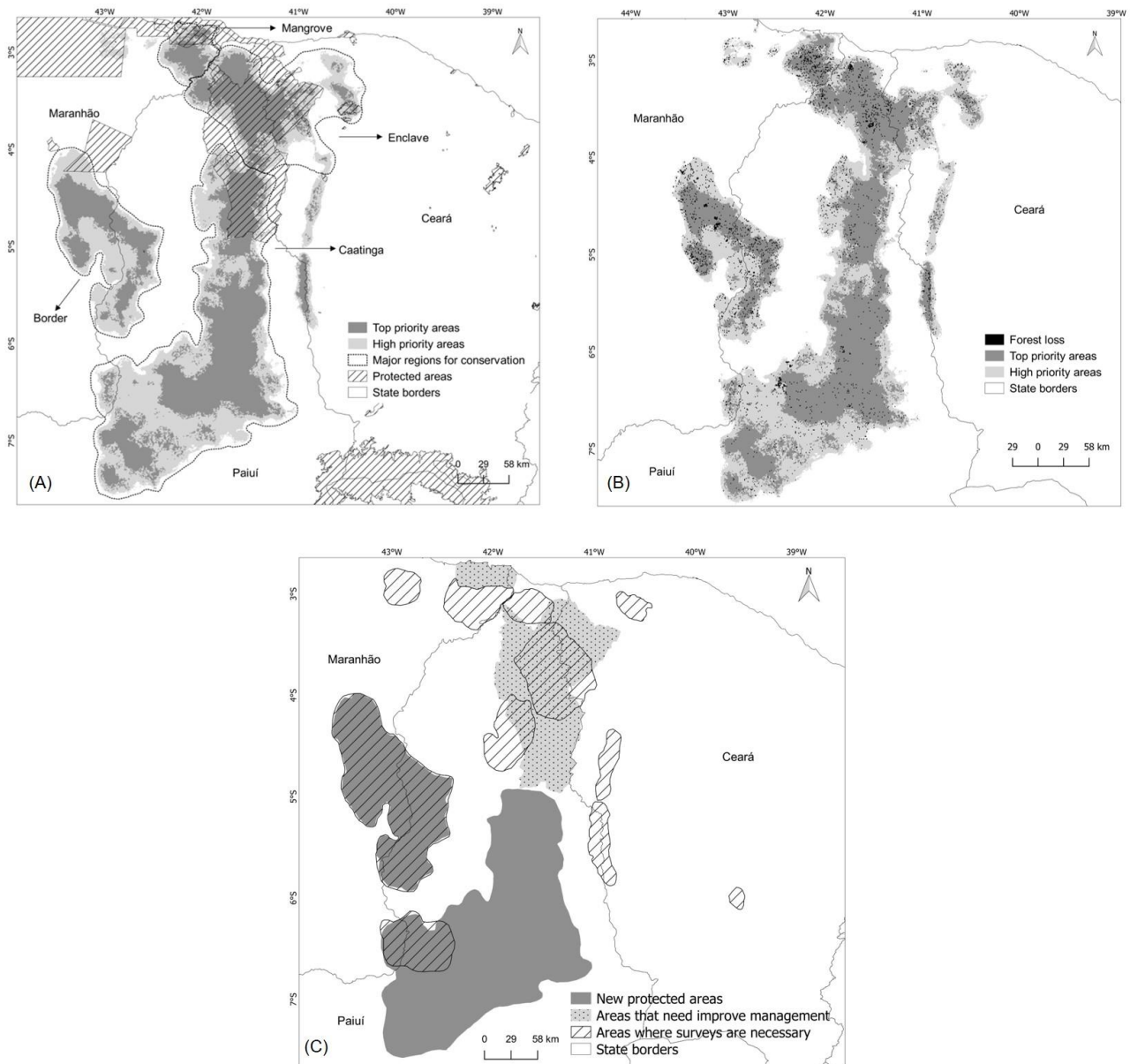


FIG. 4 (A) Priority areas for the conservation of *A. ululata*, limits of the regions referred to in the text (Mangrove, Enclave, Caatinga and Border), and existing protected areas. (B) Forest loss between 2000 and 2014 within priority areas. (C) Areas requiring survey work, new protected areas, and improved management.

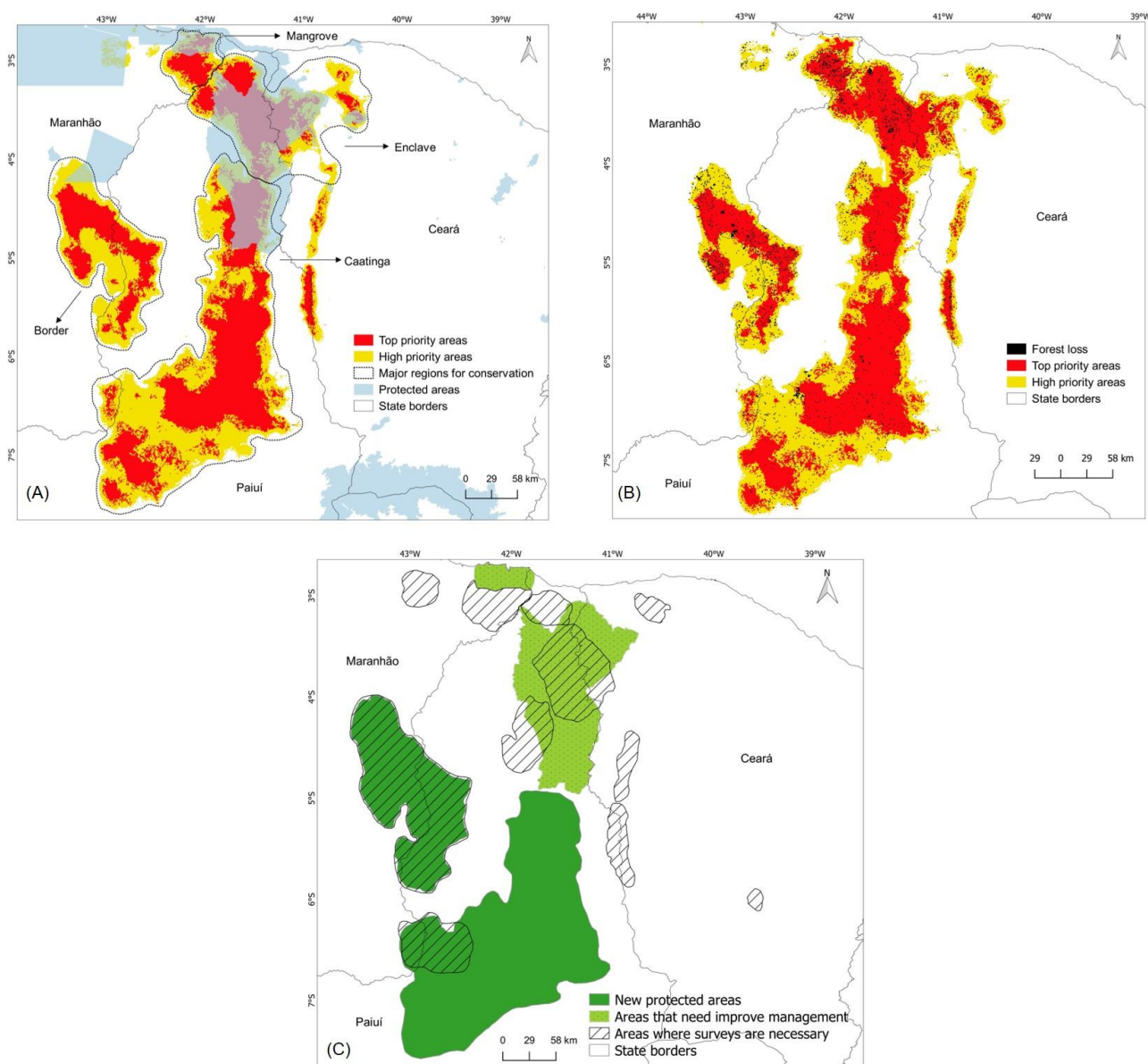
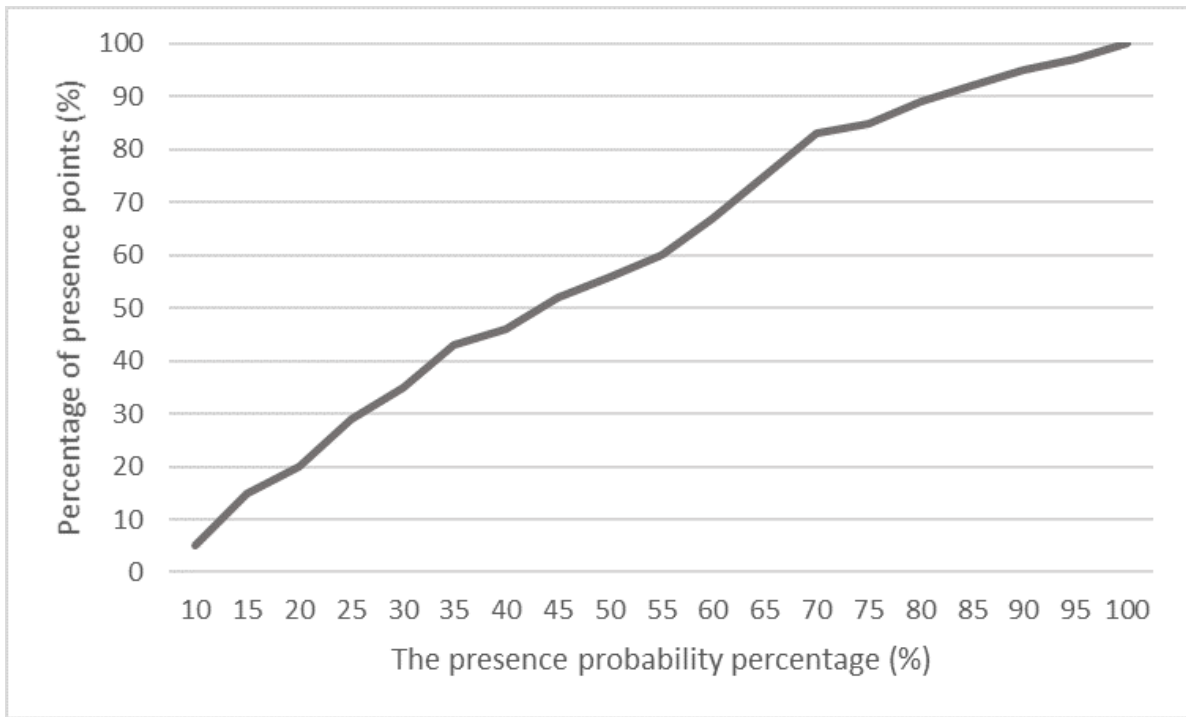


FIG. 4 (A) Priority areas for the conservation of *A. ululata*, limits of the regions referred to in the text (Mangrove, Enclave, Caatinga and Border), and existing protected areas. (B) Forest loss between 2000 and 2014 within priority areas. (C) Areas requiring survey work, new protected areas, and improved management.



460 FIG. S1 Relationship between percentage of presence points and the presence probability percentage to define the suitability threshold.